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Thermal Modelling of a Power Transformer Disc Type Winding Immersed in Mineral and Ester-Based Oils Using Network Models and CFD

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ABSTRACT This contribution presents the early results of a R&D collaboration established between the University of Cantabria and the Power Transformer Manufacturer EFACEC. This paper tests two different techniques of steady state thermal modelling applied to power transformer windings, Computational Fluid Dynamics (CFD) and Thermal-Hydraulic Network Modelling (THNM). The state of the art of thermal modelling demonstrates that these techniques have been used to calculate both average and hotspot winding temperatures by solving the winding temperature and flows profiles within the winding. THNM models have worse accuracy than CFD in the predicted results. The improvement of these THNM models is a topic of study in transformer thermal modelling. The first goal of this paper is to test the accuracy of a new calibrated THNM model of a disc-type winding immersed in mineral oil. Then, this THNM model is tested with ester-based liquids, such as a natural ester and a synthetic ester, to determine if it can be applied to these liquids without further calibrations. Finally, the cooling performance of both type of liquids is compared using only the THNM model results. The results of this work show that the THNM model developed herein gives good estimations of temperatures compared to those obtained with CFD for both types of liquids. Also, the use of alternative fluids leads to lower temperatures when considering the same oil flow rate and temperature as inlet boundary condition.

INDEX TERMS CFD, THNM, thermal modeling, power transformers, mineral oil, ester-based liquids.

I. INTRODUCTION

Oil-immersed power transformers are one of the most expensive and critical components of an electrical system. Despite being highly-efficient machines, a small fraction of the transferred power is lost in the form of heat (mainly in the windings), which must be removed. A heat-carrier dielectric fluid, generally a mineral oil, is used to remove the generated heat, and simultaneously provide electrical insulation. This liquid circulates around the windings cooling them, and thus preventing hotspots that negatively affects to the transformer lifetime. The dimensions of these cooling channels depend on the dielectric fluid properties, as well as the structural and electrical requirements, [1].

Numerical techniques such as Computational Fluid Dynamics (CFD) and Thermal Hydraulic Network Modelling (THNM) have been used by manufacturers to predict and improve the thermal and hydraulic performance of power transformers. While in CFD, the governing principles of both fluid flow and heat transfer are written in the form of partial differential equations, that are then replaced by algebraic equations and solved at discrete elements in time and space, in THNM, those same governing principles are mostly written in the form of simpler algebraic equations that rely on analytical and/or empirical coefficients, in particular in the fluid domain, where the flow profile is not solved, and therefore, singular phenomena such as hot streaks or flow

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inversions cannot be easily captured. Although both techniques have their differences, they tend to be complementary, being the THNM more attractive for design purposes due to its reduced time-to-solution and due to its easier integration with other proprietary algorithms.

During the last two decades, several authors have reported the CFD technique as a relevant tool to investigate and improve the thermal performance of power transformers windings. In the first decade, the main purpose of CFD was to determine the velocity and temperature profiles of a 2-D winding immersed in a mineral oil, [2]–[7]. More recently, the improvement of computational resources has enabled the use of 3-D models to conduct numerical investigations, allowing to capture three-dimensional phenomena that are impossible to find in 2-D models, [8]–[11]. Furthermore, other authors have used both 2-D and 3-D models to better understand and characterize the thermal-hydraulic performance of the insulation systems (oil and paper) with ester-based oils, [12], [13], as well as to evaluate the cooling efficiency of several alternative liquids, [14], [15].

Regarding the THNM technique, the first developments were carried out in the 80's and 90's. At first, those efforts resulted in the development of a hydraulic network model in Cartesian coordinates with uniform disc temperatures, [16]–[20]. At the end of the 90's, a further step was taken by modelling the geometry in cylindrical coordinates and considering both surface and internal disc temperatures, [21]. Moreover, other authors have applied the network concept to model the heat flow and the coupling between the winding temperature distribution and the hydraulic network, [22]–[27]. Nonetheless, all these models treated the heat flux in 1-D, i.e., the heat conduction in both axial and radial directions was not considered. This simplification was overcome by other authors, who have applied several numerical techniques to obtain the 2-D temperature distribution of the winding discs, [28]–[35].

On the other hand, some authors have reported THNM models that rely on the calculation of local pressure drop, friction and heat transfer coefficients. Most of these coefficients have been obtained from correlations that come from experimental data. The suitability of these expressions with transformer oil flow is however not well proved, [36]. On this account, some authors have calculated their own correlations based on CFD simulations performed for transformer oils. This is the so-called CFD calibration. For instance, in 2008, Zhang et al. determined experimentally two Nusselt correlations that were later used to calculate the convective heat transfer coefficients for zigzag cooled power transformer windings, [37]. Despite this advancement, some authors have pointed out that these networks were based on expressions obtained from a limited number of experimental cases with relatively simple flows, such as in papers [36]–[38]. To obtain more robust expressions, Wu et al, [36], [38], and Coddé *et al.* [39], have used CFD to extend the numbers of cases considered, by creating a large set of two-dimensional junction/elbow models.

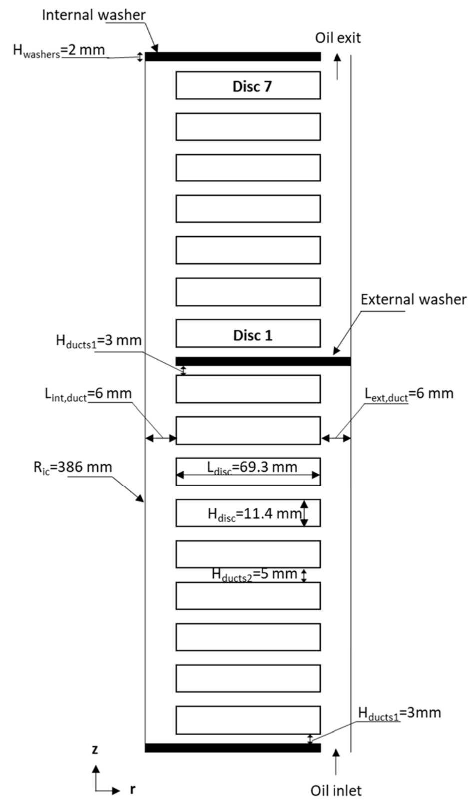


FIGURE 1. Disc-type winding geometry with dimensions.

In this contribution, a THNM model of a disc-type winding, previously developed for mineral oil, was used to perform thermal-hydraulic calculations with alternative liquids, namely a natural ester-based oil and a synthetic ester-based oil. The results were then compared with the respective results obtained from 2-D CFD simulations. The objective of this comparison is to assess the accuracy of THNM based on the deviations of the hotspot, the maximum and average disc temperatures and the mass flow rate distribution in the radial channels.

Next section presents the numerical models developed with both techniques – THNM and CFD. The results of both models are then compared and discussed. Finally, the conclusions deriving from this comparison are presented.

II. NUMERICAL MODELS

As mentioned above, two different numerical models of the selected geometry were developed using CFD and THNM techniques. Geometry, brief description of the methodologies of both techniques, common boundary conditions, material properties and cases studied are addressed below.

A. GEOMETRY

The geometry used in [40] is also considered in this paper, see Fig. 1. This geometry is a section of a disc-type winding with 16 discs divided into 2 passes. The upstream pass contains 9 discs and the downstream pass contains 7 discs. There is an arrangement of radial spacers with 5 and 3 mm height between discs, and between discs and washers, respectively. Axial spacers with 6 mm width can be found between discs and both internal and external insulation.

B. MODEL BASICS

First thermal modelling technique used in this paper is CFD. This technique is used to solve the partial differential equations (PDE) that govern both fluid flow and heat transfer. For incompressible fluid domains, the equations that state mass, momentum and energy conservation are (1-3), and for solid domains, the equation that state energy conservation is Eq. (4).

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{u}) = 0 \tag{1}$$

$$\frac{\partial (\rho \boldsymbol{u})}{\partial t} + \nabla \cdot (\rho \boldsymbol{u}\boldsymbol{u}) = -\nabla p + \mu \left(\nabla^2 \boldsymbol{u}\right) + \boldsymbol{g}(\rho - \rho_{ref}) \tag{2}$$

$$\frac{\partial (\rho c_p T)}{\partial t} + \nabla \cdot \left(\rho c_p \boldsymbol{u} T\right) = \nabla \cdot (k \nabla T) + S_E \tag{3}$$

$$\frac{\partial (\rho c_p T)}{\partial t} = \nabla \cdot (k \nabla T) + S_E \tag{4}$$

where $\rho, \boldsymbol{u}, p, \mu, \boldsymbol{g}, c_p, T, k$ and S_E of (1-4) are density, velocity field, pressure, dynamic viscosity, gravity, specific heat capacity, temperature, thermal conductivity, and volumetric heat sources, respectively.

Eqs. (1-3) are solved considering laminar flow in the fluid domain. To determine if the flow is laminar or not, Reynolds number has to be assessed. In a duct with internal flow, this parameter can be calculated using (5). According to [6], for *Re* values below 2100 the said condition holds.

$$Re = \frac{\rho u D_h}{\mu} \tag{5}$$

where D_h is the hydraulic diameter of the considered duct.

To solve the PDEs, the geometry must be discretized into smaller elements, which together compose a numerical mesh. In this work, the discretization was applied on a 2-D axisymmetric model. Several mesh independence tests have been carried out so as to prove that the influence of the chosen number of elements on the results can be neglected. A mesh with approximately 700000 quadrilateral elements was finally used. Figure 2 presents a detail of the mesh used for the study. The model developed was compared with the CFD results presented in [40] and were successfully replicated. A second-order discretization was applied to avoid diffusion errors and the solver was set with double precision in a coupled scheme. The admissible residuals were set to 1e-6 for continuity and momentum equations and 1e-9 for energy equation. The approximate solution of the PDEs was obtained using the commercial solver ANSYS Fluent®.

The second technique used is THNM. This technique relies on the conservation laws of mass, momentum and energy, as in the CFD technique. In THNM models, there is a coupling between two different networks: a hydraulic network

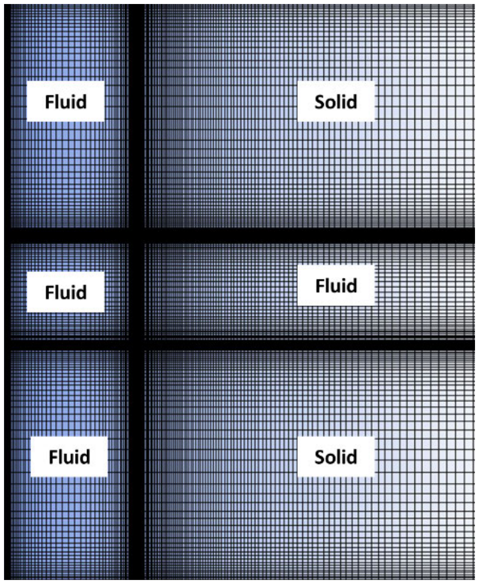


FIGURE 2. Meshing detail in a T-junction of the CFD model.

and a thermal network. The establishment of these two networks stems from the hydraulic-electric analogy and the thermal-electric analogy, respectively, [41]. In most THNM models, the solid domain is solved in the same way as in a CFD model. This means that both models have the same numerical accuracy when computing the disc temperature distribution if the same numerical mesh is applied. However, since the fluid domain (i.e., the cooling channels domain) is not solved in the same way, deviations between both models are inherent. Instead of solving the partial differential equations of momentum and energy conservation, THNM models solve the fluid domain by means of one-dimensional coefficients (e.g., frictional pressure drop coefficients, local pressure drop coefficients and Nusselt coefficients), which have a major influence on the magnitude of the deviations between both models. Figure 3 shows the discretization used for the developed model.

THNM relies on two main approaches: fully developed flow is assumed in the cooling channels and perfect thermal and hydraulic mixing is considered in the channels and junctions of the fluid domain.

In THNM models, since frictional and local pressure drops are treated separately, i.e., there are distinct expressions to compute frictional and local pressure drops, two different coefficients must be used. In the case of the frictional pressure drop, the friction coefficient λ must be accounted for. In isothermal laminar flow, this coefficient is analytical and can be expressed as a function of both Poiseuille and Reynolds number, (6):

$$f(Re) = \frac{C}{Re} \tag{6}$$

where C is the Poiseuille number and Re is the Reynolds number.

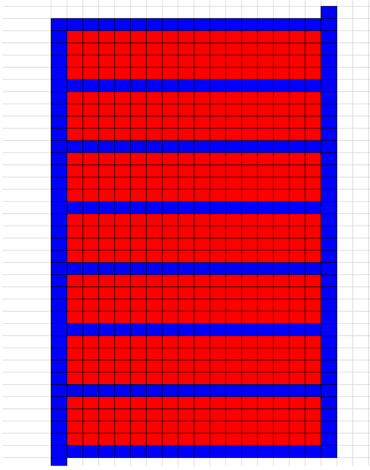


FIGURE 3. Geometry discretization applied in THNM model.

For local pressure drops, local pressure drop coefficients can be calculated using correlations obtained from experimental data, as presented in [37], or through data sets obtained from CFD simulations, [38], [39]. These two methods are also used to compute the Nusselt coefficients, [36].

In the present work, a thermal and hydraulic CFD calibrated THNM model is used to investigate how dependent both momentum and heat transfer coefficients are in relation to the fluid considered.

The presented THNM model was developed independently by the authors from the University of Cantabria. However, the local pressure loss coefficients were extracted in close collaboration with EFACEC using the same methodology applied in its proprietary THNM model, which is not discussed in this work.

C. BOUNDARY CONDITIONS

To compare the results of both CFD and THNM techniques, the same boundary conditions are applied in both models. A brief description of these boundary conditions is presented here.

All exterior solid walls of the geometric model are considered adiabatic surfaces, (7).

$$-\boldsymbol{n} \cdot (k\nabla T) = 0 \tag{7}$$

At all the walls of the cooling channels, the no-slip condition is applied, (8).

$$u_{wall} = 0 \tag{8}$$

A constant and uniform heat loss distribution along the entire winding is assumed, (9).

$$Q_{disc} = Q_0 \tag{9}$$

At the inlet of the upstream pass, uniform velocity and temperature profiles are considered, (10) and (11).

$$u_{inlet} = u_0 \tag{10}$$

$$T_{inlet} = T_0 \tag{11}$$

TABLE 1. Physicochemical properties of the fluids.

	Mineral oil	Natural ester	Synthetic ester
ρ (kg/m^3)	1098.72 -0.712T	1109.2 -0.653T	1185.2 -0.7333T
c_p $(J/(kg \cdot K))$	807.163 +3.58T	1273.15 +1.952T	1242.38 +2.198T
k $(W/(m \cdot K))$	0.1509 -7.101e-5T	0.1317+4.14e-4T-8.86e-7T^2	9.71e-2+3.74e-4T -7.25e-7T^2
μ $(Pa \cdot s)$	0.08467-4e-4T+5e-7T^2	7.99-6.64e-2T+1.84e-4T^2-1.71e-7T^3	0.2565-1.3e-3T +1.68e-6T^2

TABLE 2. Cases studied.

	Cooling regime	
	ON	OD
u_{inlet} (m/s)	0.0961	0.2451
T_{inlet} (K)	337.95	337.95
Q_{disc} $(W/disc)$	1577.41	1577.41

At the outlet of the downstream pass, a uniform pressure profile is considered, (12).

$$p_{outlet} = 0 \tag{12}$$

D. MATERIALS PROPERTIES

The physicochemical properties of the fluids involved in the physics considered are shown in Table 1. As can be seen in this table, the temperature dependence of the properties is expressed as a function of the fluid temperature in Kelvin.

Regarding the solid thermal properties, this material is modelled with an equivalent thermal conductivity. That is, the thermal conduction behavior of the winding discs is represented using an equivalent radial and axial conductivity of 0.646 and 3.751 W/(m·K), respectively, [40].

III. CASES STUDIED

In this work, the deviations that exist between a CFD model and a calibrated THNM model are tested with the geometry previously described. Temperature and mass flow deviations will be computed for mineral oil. Moreover, the accuracy of the same THNM model will be tested for alternative liquids, with the aim of developing a modelling tool that fits for mineral oil as well as alternative dielectric liquids.

Two different cases have been tested for each fluid in terms of the transformer cooling regime. The values considered for the boundary conditions in both cases are extracted from [40]. They correspond to typical operating conditions, inlet velocity and temperature, of an ON and OD power transformer immersed in mineral oil, see Table 2. For the alternative fluid cases, same inlet velocity and temperature as those for mineral oil are considered.

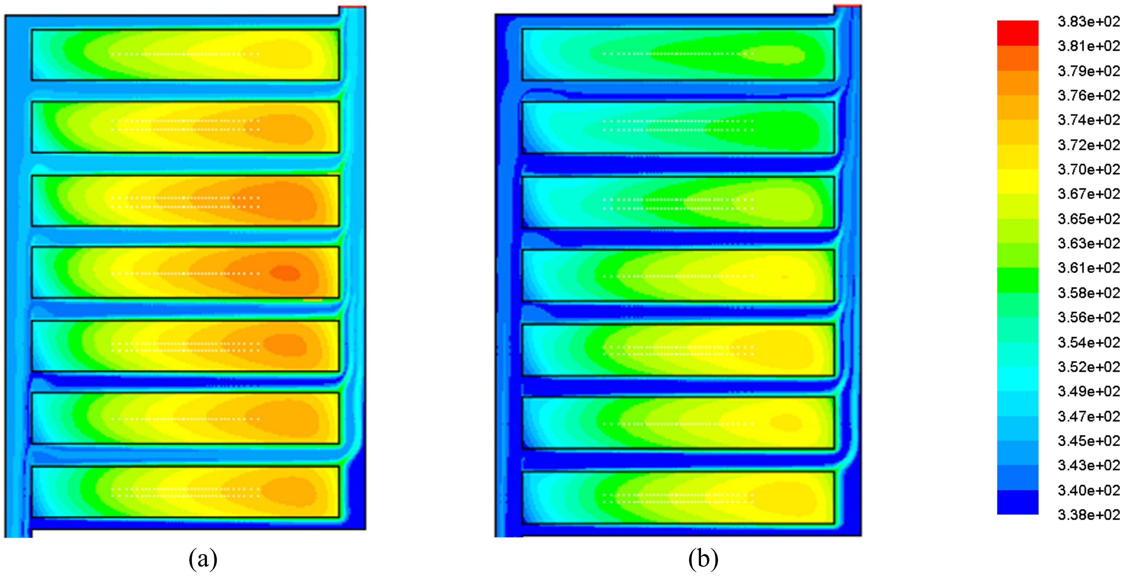


FIGURE 4. Temperature distribution in the winding. (a) ON case, (b) OD case.

TABLE 3. Temperatures and their location of the mineral oil.

	ON case			OD case		
	T_{avg} (ºC)	HST (ºC)	HS location	T_{avg} (ºC)	HST (ºC)	HS Location
CFD	94.5	105.8	Disc 4	86.6	98.3	Disc 3
THNM	96.8	104.0	Disc 4	90.4	100.1	Disc 2

Since these conditions have a *Re* less than 465, the flow regime is laminar for all cases. Only the results of the second pass are analysed. The first pass of the winding is taken into account in order to reduce the impact of introducing uniform velocity and temperature profiles at the inlet. That is, it could be regarded as a preconditioning pass.

A. CFD VS THNM WITH MINERAL OIL

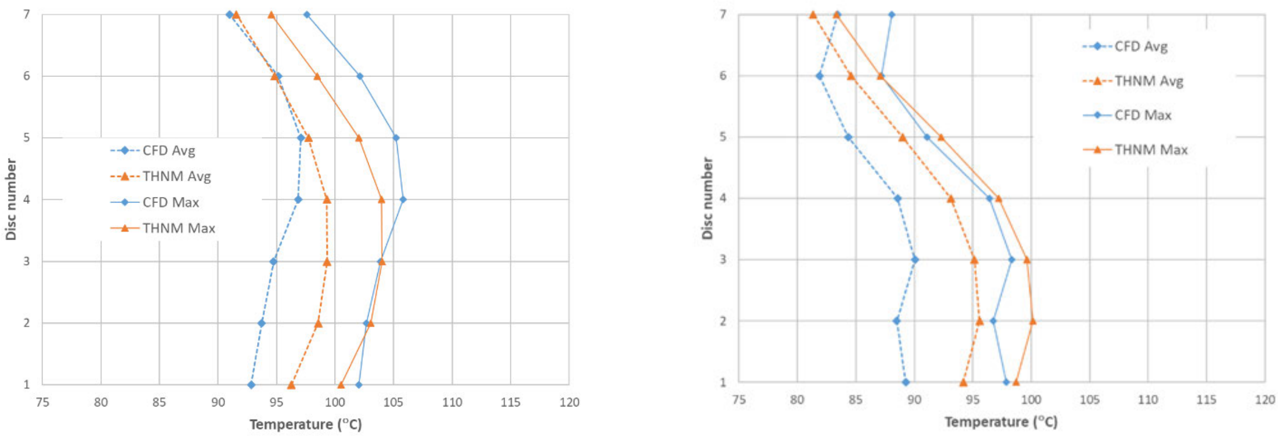
First fluid considered for CFD and THNM comparison is mineral oil. Figure 4 shows the temperatures obtained in the winding with the CFD model. The highest temperature region is located in the middle discs in the ON case whereas in the OD case is located in the bottom zone of the pass.

The temperatures, average and hotspot, including the hotspot location, computed by CFD and THNM for both ON and OD cooling regimes with mineral oil as dielectric fluid are presented in Table 3. This table shows a deviation between CFD and THNM of +2.3°C in the average temperature and −1.8°C in the hotspot temperature for the ON case. For the OD case, the respective deviations are +3.8°C and +1.8°C. From the foregoing, it can be concluded that the higher temperature deviations occur with the higher velocities. This can be explained as follows: keeping in mind that the higher the fluid velocity is, the less developed the flow is in short ducts (e.g. the radial channels of the winding), the fulfillment of the fully developed flow simplifying condition in THNM will worsen with the increase of the liquid velocity. This is the reason why the results of the THNM model increase their deviations in comparison with those of the CFD model with the increase of the inlet velocity. This observation is also endorsed when comparing the hotspot location, which was well predicted exclusively for the ON case.

In addition, the trends of the average and maximum temperature profiles, shown in Figure 5, are also different. However, a good agreement of the maximum disc temperatures is observed between both types of models. Even more, an overestimation of T_{avg} is obtained in the THNM model, especially for OD case.

The deviations between the temperature profiles from CFD and THNM are caused by the fact that THNM models are not able to capture local phenomena such as hot streaks or non-uniform velocity profiles. These effects entail differences in the heat transfer of each disc, leading to a slightly different profile in the case of CFD with respect to the THNM profile.

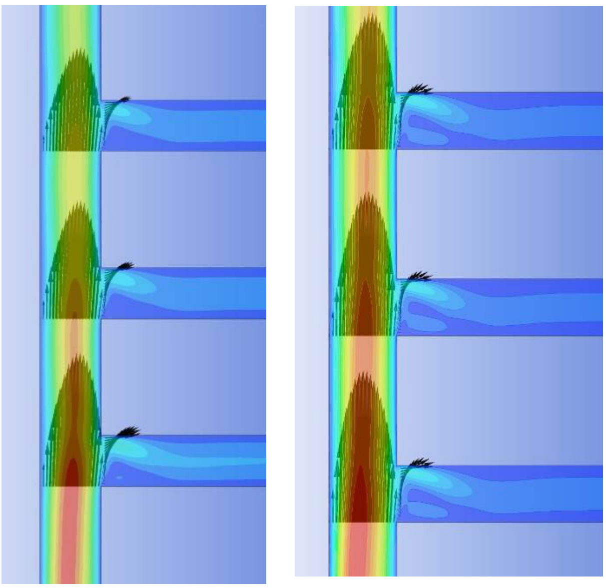
Regarding the mass flow distribution in the channels, Figure 6 shows the velocity profiles at the inlet of the radial channels. It shows the distortion of the velocity profile at the inlet of these channels caused by the separating flow. The flow at the inlet of radial channels is pushed to the top part of the channel. This effect, which is more pronounced at higher velocities, causes a region of low velocity at the bottom of these inlets, where the temperature of the fluid locally



(a) ON case

(b) OD case

FIGURE 5. Average and maximum disc temperature distributions for mineral oil.



(a) ON case

(b) OD case

FIGURE 6. Velocity at radial channels inlet.

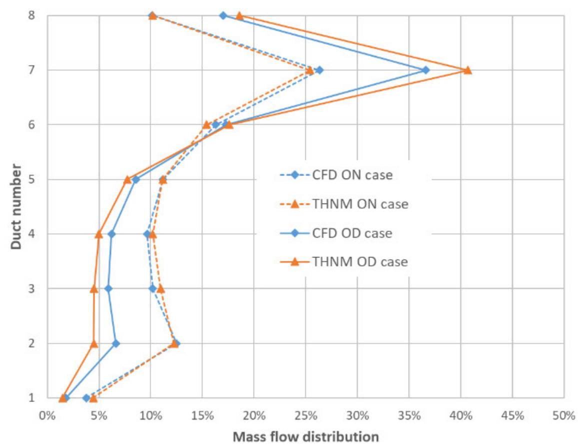


FIGURE 7. Mass flow distributions for mineral oil.

increases. Finally, Figure 7 shows the mass flow distributions, radial channel flow over total flow, for both models and regimes, having a good agreement between them.

The thermal assumptions of the THNM modelling make its temperature profiles not match with those of CFD with the same accuracy seen for flow rates.

Notwithstanding the deviations observed, the accuracy of the presented THNM model agrees with other THNM models existing in the literature, as well as with the instruments and procedures used to experimentally measure these values.

B. CFD VS THNM WITH ALTERNATIVE LIQUIDS

Both winding temperatures, average and hotspot, including the hotspot location, computed by CFD and THNM for both ON and OD cooling regimes with natural and synthetic ester as dielectric fluid are presented in Table 4.

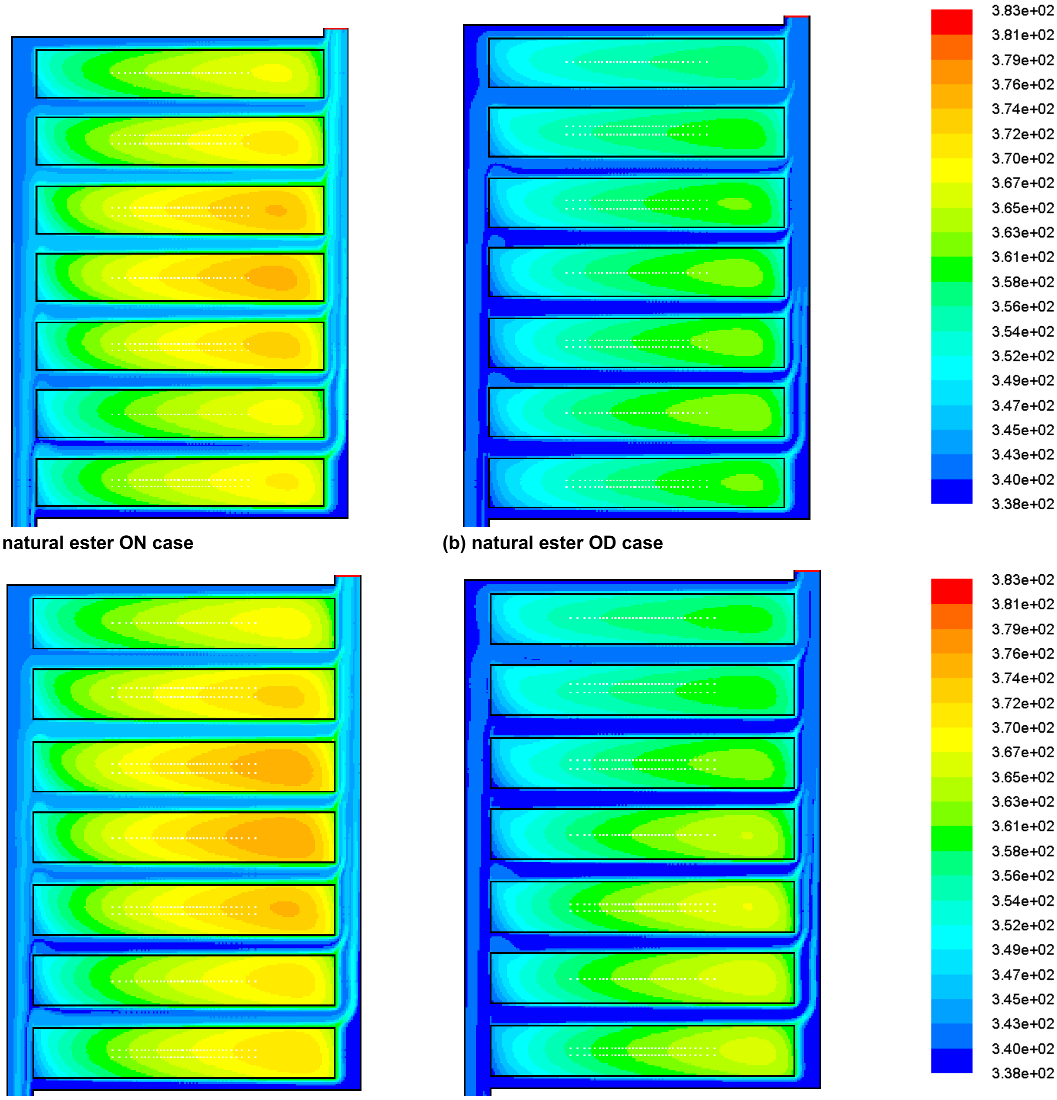
For the natural ester, Table 4 shows a deviation between CFD and THNM of +1.2°C in the average temperature and −3.5°C in the hotspot temperature for the ON case. For the OD case, the respective deviations are +2.5°C and +0.0°C.

For the synthetic ester, Table 4 shows a deviation between CFD and THNM of +1.9°C in the average temperature and −2.7°C in the hotspot temperature for the ON case. For the OD case, the respective deviations are +2.7°C and −0.2°C.

Figure 8 shows the temperature distributions in the winding obtained for natural and synthetic ester. As in the case of mineral oil, the middle discs present the highest temperatures, especially in the ON case. In addition, the effect of hot streaks is more highlighted in the ON case.

As in the previous case, Figures 9 and 10 show the temperature and mass flow comparisons between the two techniques for the alternative liquids.

Regarding the temperature distribution, as shown in Figure 10, THNM overestimates the average temperatures in OD case. However, its agreement in ON case is better.



(a) natural ester ON case

(b) natural ester OD case

(c) synthetic ester ON case

(d) synthetic case OD case.

FIGURE 8. Temperature distribution in the winding.

TABLE 4. Temperatures and their location of the alternative liquids.

		ON case			OD case		
		T_{avg} (ºC)	HST (ºC)	HS location	T_{avg} (ºC)	HST (ºC)	HS location
Natural ester	CFD	91.2	101.8	Disc 4	82.2	89.8	Disc 2
	THNM	92.4	98.3	Disc 4	84.7	89.8	Disc 3
Synthetic ester	CFD	92.2	103.2	Disc 4	84.3	94.2	Disc 3
	THNM	94.1	100.5	Disc 4	87.0	94.0	Disc 2

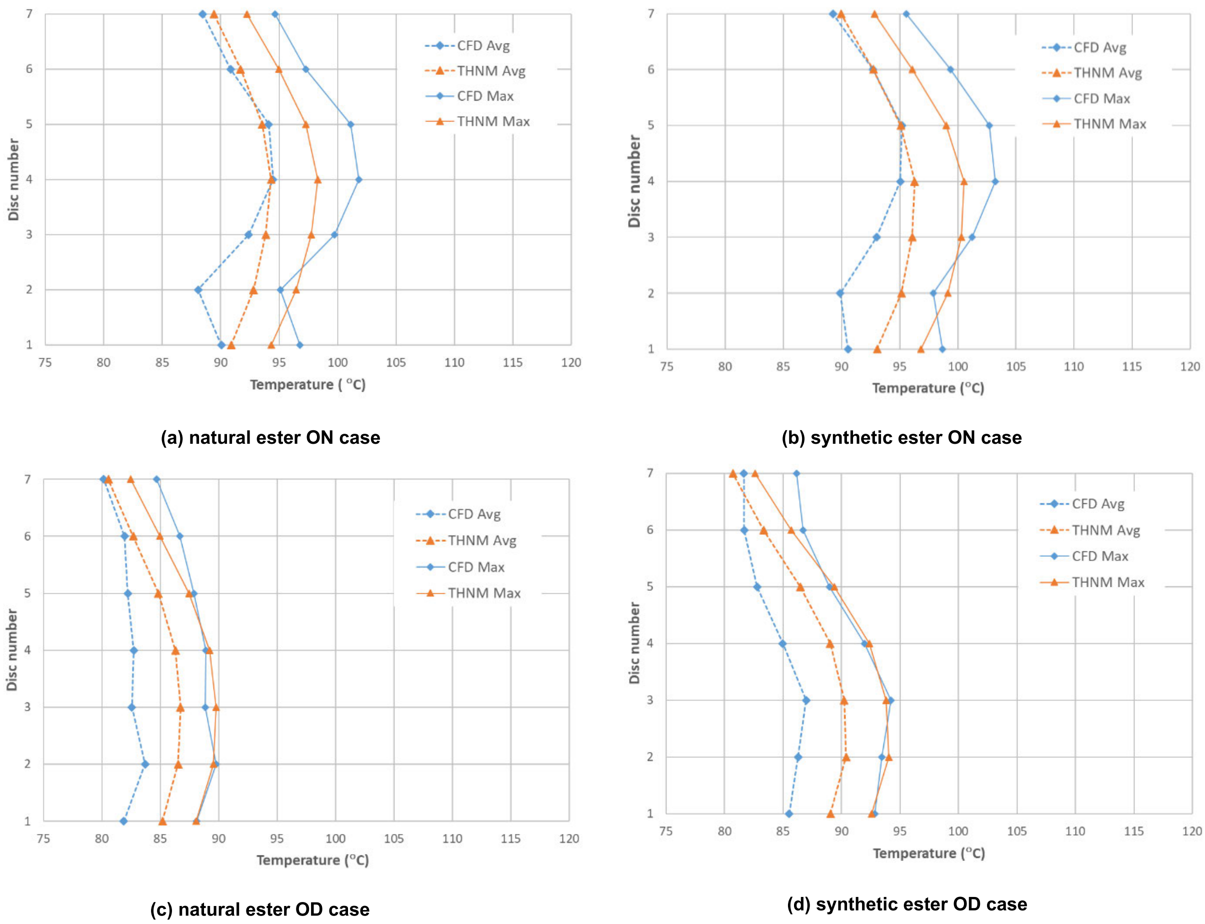
Looking at the maximum temperatures, the hotspot temperature in ON case is underestimated whereas in OD case has good accuracy.

Finally, as can be seen in Figure 10, the mass flows distribution of the THNM model has good agreement with the CFD results for both liquids and both cooling modes.

C. MINERAL OIL VS ESTER LIQUIDS COOLING PERFORMANCE

Finally, a comparison of the cooling performance of the liquids has been made using THNM results.

Average and maximum winding temperatures of the three liquids are presented in Table 5. Regarding the ON regime,



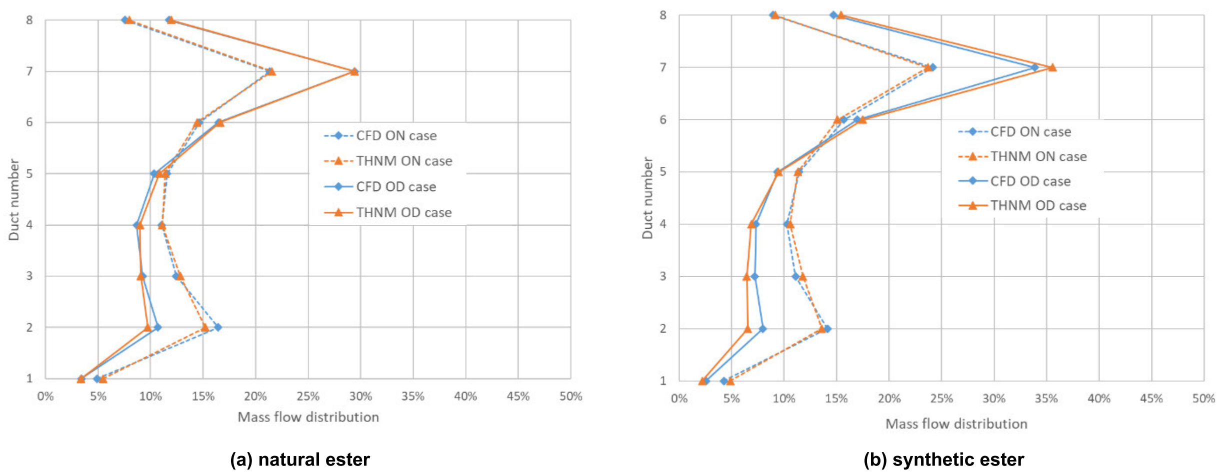
(a) natural ester ON case

(b) synthetic ester ON case

(c) natural ester OD case

(d) synthetic ester OD case

FIGURE 9. **Distributions of average and maximum temperatures.**



(a) natural ester

(b) synthetic ester

FIGURE 10. **Mass flow distributions.**

both average and hotspot winding temperatures are lower for the ester-based liquids than for the mineral oil, being this deviation, for both natural and synthetic ester, respectively, −4.4°C and −2.7°C for the average, and −5.7 and −3.5°C for the hotspot.

Considering the OD flow regime, these deviations increase, which means that under these conditions and comparing against the mineral oil, the ester-based fluids are even more cooling-efficient. These deviations are −5.7° C and −3.4°C for average winding temperature, and −10.3°C and −6.1°C

TABLE 5. Average and maximum temperatures of the liquids using THNM.

	ON case		OD case	
	T_{avg} (ºC)	HST (ºC)	T_{avg} (ºC)	HST (ºC)
Mineral oil	96.8	104.0	90.4	100.1
Natural ester	92.4	98.3	84.7	89.8
Synthetic ester	94.1	100.5	87.0	94.0

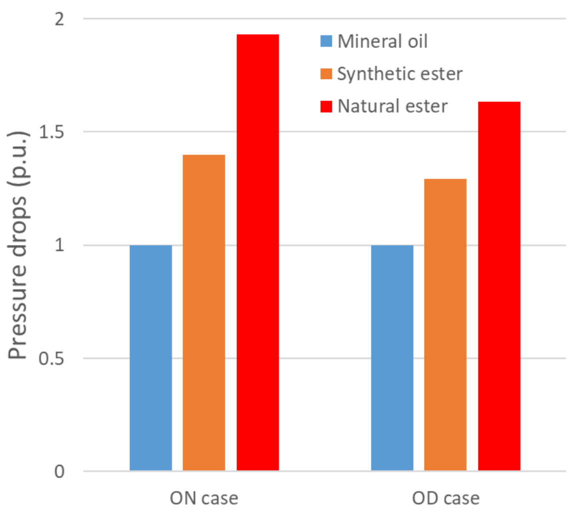


FIGURE 11. Pressure drops in both regimes.

for maximum winding temperature for both natural and synthetic esters, respectively.

However, since the ester-based liquids are more viscous than mineral oil, the pressure drop observed in the downstream pass is higher for the alternative fluids, as can be seen in Figure 11. An increase of 93.2% and 39.8% of the pressure drop is observed for natural and synthetic ester respectively in ON regime. Regarding the OD flow regime, the increase of the observed pressure drop becomes 63.3% for natural ester and 29.09% for synthetic ester. As a result of these higher pressure drops the total flow rate will decrease.

Finally, to properly compare the cooling performance of the different liquids, in the ON case, inlet velocities of the alternative fluids have been adjusted until the same pressure drop as that of the mineral oil is obtained. In this way, mineral oil leads to slightly lower hot-spot temperatures, as can be appreciated in Table 6. In fact, synthetic ester produces similar temperatures as those of mineral oil and it is the natural ester the oil that yields higher temperatures: 2.3 °C and 1.9 °C higher for the average and maximum winding temperatures, respectively.

IV. CONCLUSION

In this paper, two different techniques have been used to compute the thermal behavior of transformers disc type windings. The first technique, CFD, computes in detail the temperature

TABLE 6. Average and maximum temperatures of the liquids using THNM.

	ON case	
	T_{avg} (ºC)	HST (ºC)
Mineral oil	96.8	104.0
Natural ester	99.1	105.9
Synthetic ester	97.0	104.0

and velocity fields arising in the transformer winding and its accuracy has been proved for years. The second technique, THNM, is a simplified model that relies on some assumptions that reduces its accuracy but produces results much faster than CFD, which makes it an interesting tool, mainly for design purposes.

In this work, the THNM performance for three fluids (mineral oil, natural ester and synthetic ester) subjected to two cooling regimes, ON and OD, was compared against CFD.

In the case of mineral oil, the THNM model results of the two cooling regimes show that the mass flow distributions through the radial channels are similar to the ones obtained with CFD. Regarding the temperatures, the deviations are higher. However, these deviations could be acceptable in the range of the operating temperatures. Consequently, the validity of the THNM model is accomplished for mineral oil.

Then, the THNM model, which is calibrated for mineral oil, has been tested with two different alternative fluids, a natural ester and synthetic ester. In both cases, the accuracy of the temperature results was acceptable since all the deviations are similar to those observed for the mineral oil. Moreover, the predicted mass flow distribution through the radial channels in the THNM model has a good agreement with the CFD results. Then the calibrated THNM used in this work fits for all three fluids considered. However, more research is necessary concerning the behavior of alternative dielectric liquids such as natural and synthetic esters in a full winding of a power transformer or when considering the complete cooling circuit. These topics are to be kept in mind as the next steps in continuing this line of work.

With respect to the cooling performance of the liquids, natural ester gives the lowest average and hotspot temperatures but with the highest pressure drop. On the other hand, mineral oil requires less driving force since it produces the lowest pressure drop, but also the highest temperature in the windings. Synthetic ester gives intermediate values, decreasing the temperatures obtained from mineral oil with a lower increase of pressure drop than that of natural ester. However, this study is the first step to analyze the cooling performance of alternative fluids and more studies in the matter should be carried out, since the viscosity affects the inlet boundary conditions.

Summarizing, the THNM model developed could be used directly for mineral oil, as well as alternative fluids. In fact, this technique has been used to compare the cooling performance of three different liquids.

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